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13. ABSTRACT

Superevents are long-lived (~40 days at 1 AU) ~10-MeV proton events that originate in episodes of intense solar activity characterized by major coronal mass ejections (CMEs) and individual solar energetic particle (SEP) events. Superevents exhibit only weak intensity variation with heliolongitude. They propagate to the outer heliosphere at speeds above that of the average solar wind, and, at Pioneers 10 and 11, prominent superevents are generally associated with strong interplanetary shocks. For the period from 1974 to 1985, we find that superevents are not reliable signatures of the onsets of long-term steps in the modulation record of >1-GV galactic cosmic rays (GCRs) at 1 AU. Of six intense superevents during this interval, one occurred coincident with the onset of a step (June-July 1982), two occurred midway through step decreases, and three occurred at the ends of step decreases. Two step decreases during this period began in conjunction with relatively weak SEP activity. Thus the largest superevents occurring from 1974 to 1985 were neither necessary nor sufficient conditions for long-term GCR intensity steps and therefore were not closely related to the global merged interaction regions that have been identified with such steps. In terms of convection/diffusion models of cosmic ray modulation, the poor association of the largest superevents with long-term GCR intensity decreases during this period suggests that the background level of more frequently occurring, and less energetic, CMEs is more important for establishing the 11-year cycle than are the sporadic, and relatively short-lived, outbreaks of major CME activity that give rise to superevents.

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Superevents and Cosmic Ray Modulation, 1974–1985

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Superevents are long-lived (~40 days at 1 AU) ~10-MeV proton events that originate in episodes of intense solar activity characterized by major coronal mass ejections (CMEs) and individual solar energetic particle (SEP) events. Superevents exhibit only weak intensity variation with heliolongitude. They propagate to the outer heliosphere at speeds above that of the average solar wind, and, at Pioneers 10 and 11, prominent superevents are generally associated with strong interplanetary shocks. For the period from 1974 to 1985, we find that superevents are not reliable signatures of the onsets of long-term steps in the modulation record of >1-GV galactic cosmic rays (GCRs) at 1 AU. Of six intense superevents during this interval, one occurred coincident with the onset of a step (June-July 1982), two occurred midway through step decreases, and three occurred at the ends of step decreases. Two step decreases during this period began in conjunction with relatively weak SEP activity. Thus the largest superevents occurring from 1974 to 1985 were neither necessary nor sufficient conditions for long-term GCR intensity steps and therefore were not closely related to the global merged interaction regions that have been identified with such steps. In terms of convection/diffusion models of cosmic ray modulation, the poor association of the largest superevents with long-term GCR intensity decreases during this period suggests that the background level of more frequently occurring, and less energetic, CMEs is more important for establishing the 11-year cycle than are the sporadic, and relatively short-lived, outbreaks of major CME activity that give rise to superevents.

1. INTRODUCTION

Cosmic ray modulation during the maximum of solar cycle 21 (1978 to 1982) proceeded in a series of steps [*McDonald et al.*, 1981*a*; *Burlaga et al.*, 1984] that were observed in turn at earth and the Voyager and Pioneer spacecraft. At both 1 AU and at Pioneer 10 (P-10), which moved from ~10 to 30 AU during this interval, the steps consisted of decreases of the galactic cosmic ray (GCR) intensity lasting ~6 months followed by plateaus or weak recoveries. Such steps had previously been reported for cycles 18 [*Morrison*, 1956] and 19 [*Lockwood*, 1960]. Subsequently, steps have been reported for cycle 22 [*Burlaga et al.*, 1991, 1993; *McDonald et al.*, 1993].

The solar wind structures that are associated with modulation steps are called merged interaction regions (MIRs) [*Burlaga et al.*, 1985] or, more precisely, global merged interaction regions (GMIRs) [*McDonald et al.*, 1991, 1993; *Burlaga et al.*, 1993]. GMIRs are enhanced magnetic field regions produced by the coalescence and entrainment [*Burlaga et al.*, 1983] of transient and corotating slow-speed streams by corotating high-speed streams and fast coronal mass ejections (CMEs). GMIRs are pictured schematically as "shells" that envelop the Sun to inhibit the propagation of GCRs into the heliosphere [*Burlaga et al.*, 1984, 1991]. Since MIRs may form in a variety of ways, there is no unique magnetic field (B) configuration associated with GMIRs [*Burlaga et al.*, 1993] at a given spacecraft. Moreover, the evolution of B at a single point is inadequate to reveal the presence of a global topology. A local MIR or LMIR [*Burlaga et al.*, 1993] would result in only a transient depression of GCR intensity, as particles could quickly "backfill" around the barrier. Thus, in effect, GMIRs are defined to be the large-scale solar wind structures that produce step decreases [*McDonald et al.*, 1993].

While the interplanetary disturbances that give rise to long-term step decreases have been studied at length, the solar origins of these disturbances have received relatively little attention. *Burlaga et al.* [1984] concluded that the relative efficacy of many small CMEs vs. a few major disturbances for long-term modulation was an open question. The concept of modulation via a long-lived "cloud" of "magnetic inclusions" can be traced to *Morrison* [1956] and *Newkirk et al.* [1981], while the picture of modulation via a few powerful discrete disturbances, such as individual Forbush decreases, can be traced to *Lockwood* [1960] and, more recently, *McDonald et al.* [1981*b*] [cf. *Van Allen and Mihalov*, 1990].

A detailed study of solar activity at the time of the mid-1982 GCR step decrease favored a key role for a small number of large disturbances. In their analysis of this period, *Cliver et al.* [1987] identified four major eruptive (CME-associated) flares that could be plausibly associated with pairs of Forbushlike decreases observed at the Pioneer 10 and 11 spacecraft on opposite sides of the heliosphere. They found that June and July 1982 corresponded to a local maximum in the rate of "important" CMEs and noted the concomitant occurrence of a superevent [*Müller-Mellin et al.*, 1986] in the energetic particle population at 1 AU.

Superevents are ~10 MeV proton events characterized by long durations (~40 days) and weak intensity variation with heliolongitude [*Müller-Mellin et al.*, 1986]. The most prominent superevents originate in extended episodes (0.5 to 2 months) of fast CMEs and solar energetic particle (SEP) events from single active regions or from narrow ranges of active longitudes [*Dröge et al.*, 1992]. Superevents are initially observed in the inner heliosphere and propagate to the outer heliosphere. From the midpoints of super-event profiles at successive radial distances, *Dröge et al.* [1992] determined

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transit speeds of $\sim$700–1000 km s^{-1} for five prominent superevents occurring between 1974–1985. If the onsets of the superevents at 1 AU are used instead of the mid-point in the speed determinations, the resultant lower limit speeds to P-10 for these five superevents range from 430–750 km s^{-1}. These speed values are comparable to or greater than typical annual averages of the solar wind observed near solar maximun [e.g., *Gosling et al.*, 1976]. In the outer heliosphere, superevents represent a mixture of SEPs and particles accelerated locally at interplanetary shocks [*Dröge et al.*, 1992; cf. *McDonald and Selesnick*, 1991].

A series of association studies indicates that superevents represent particularly strong transient disturbances of the heliosphere. In general, the presence of fast (>400-km s^{-1}) CMEs during superevents can be inferred from the nearly 100% association between individual SEP events and such CMEs [*Kahler et al.*, 1984]. *Cane and Stone* [1984] showed that the more intense SEP events are also associated with strong interplanetary shock waves. To complete the chain of associations linking SEPs, fast CMEs, and interplanetary shocks (within 1 AU), *Sheeley et al.* [1985] and *Cane et al.* [1987] established a close correspondence between fast CMEs and interplanetary shocks. In the simplest paradigm linking these phenomena, fast CMEs serve as pistons to drive coronal/interplanetary shocks at which SEPs are accelerated.

Because superevents (1) originate in episodes of intense eruptive solar activity leading to strong interplanetary disturbances; (2) represent global disturbances, at least in azimuth; and (3) have been linked to the onset of a long-term step decrease in one case (mid-1982), they are attractive candidates to be "signatures" of GMIRs [*Flückiger*, 1991; *Dröge et al.*, 1992; cf. *McDonald and Selesnick*, 1991; *McDonald et al.*, 1993]. However, the June–July 1982 period is the only step for which solar activity has been investigated in detail. It remains to be shown either that every step decrease is initiated by intense SEP activity or that all superevents give rise to steps. In addition, the speed at which the modulation region propagated outward during cycle 21 was generally $\sim$400 to 500 km s^{-1} [*McDonald et al.*, 1981*a*; *Lockwood and Webber*, 1984], more characteristic of ambient flows than of fast interplanetary shocks [e.g., *Mihalov*, 1985] and superevents. Thus, while linking GCR intensity steps and GMIRs with superevents is appealing, a general study of the relationship of superevents to long-term steps is warranted.

In this study we examine the role of the interplanetary disturbances associated with superevents in establishing the 11-year intensity variation of >1-GV cosmic rays at 1 AU for the period 1974–1985. If the transient disturbances associated with superevents are "drivers" of GCR modula-

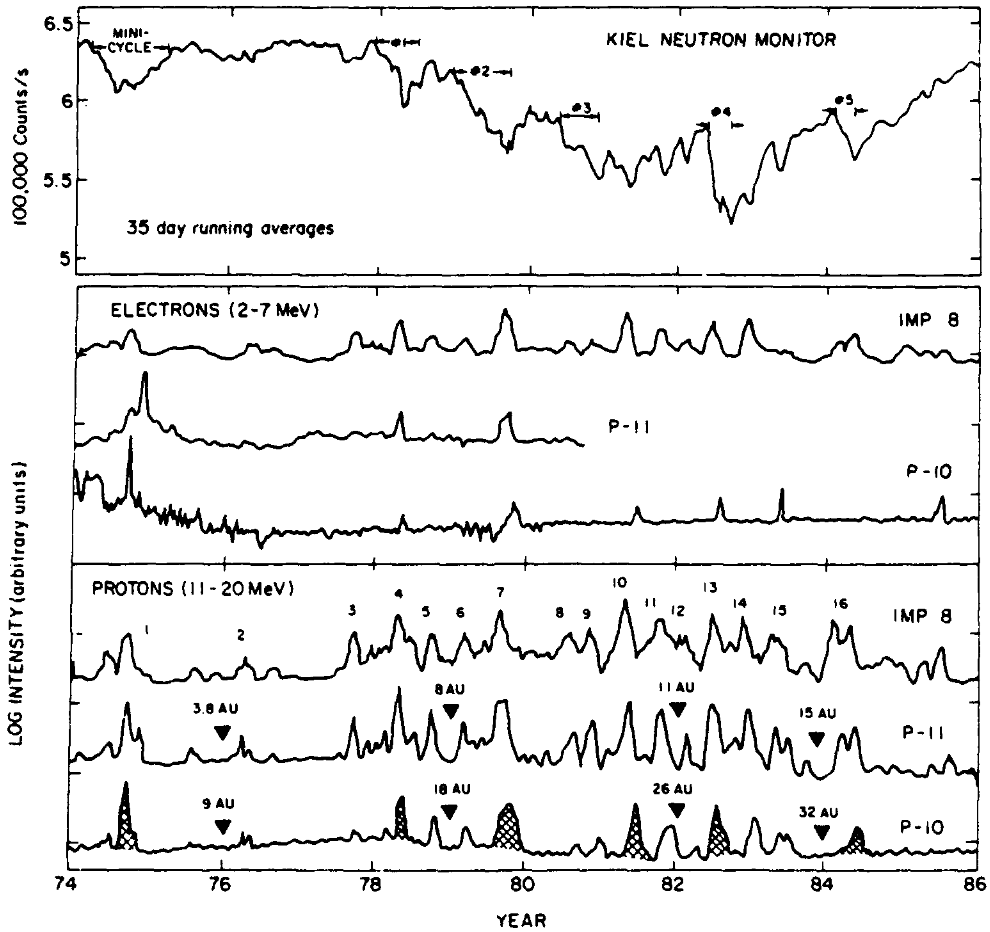

Fig. 1. Smoothed time-intensity profiles of Kiel neutron monitor data (top panel) and interplanetary particle fluxes (bottom panels; top to bottom: IMP 8, P-11, P-10, 2- to 7-MeV electrons; IMP 8, P-11, P-10, 11- to 20-MeV protons). The times of a modulation minicycle and five prominent steps are indicated in the top panel. The particle intensity scales in the bottom panels have been adjusted for each spacecraft to make the plots appear similar. The cross-hatched peaks in the P-10 proton trace indicate the superevents considered in this study. The superevent numbers follow the designations of *Dröge et al.* [1992], from whom this figure was adapted.

tion, then, by analogy with single Forbush decreases, we would expect the largest such events to occur preferentially at the onsets of long-term intensity decreases, as was the case in mid-1982. Thus our analysis consists of a comparison of interplanetary particle flux profiles and neutron monitor traces at the times of step decreases and intense superevents. While our focus is on the relationship of superevents to step decreases at 1 AU, we will also make comparisons, whenever possible, between superevent time-intensity traces and the published modulation records from deep-space probes. The analysis is presented in section 2, and the results are discussed in section 3.

2. ANALYSIS

2.1. Overview

Figure 1, adapted from *Dröge et al.* [1992], gives a synoptic view of GCR modulation at 1 AU and particle events (2- to 7-MeV electrons and 11- to 20-MeV protons) as observed in turn at IMP 8, Pioneer 11 (P-11), and P-10. The top panel contains 35-day running averages of Kiel neutron monitor data. The times of a "minicycle" [*Garcia-Munoz et al.*, 1977] and five modulation steps in the GCR intensity are indicated. Steps 1 to 4 have previously been identified by other authors [*McDonald et al.*, 1981*a*, 1991, 1993; *Burlaga et al.*, 1984]. The proton and electron data at IMP 8, P-11, and P-10 in the lower panels of Figure 1 represent 54-day, 27-day, and 15-day running averages, respectively. When averaged in this manner, the proton profiles look similar for all radial distances considered. This aids in the identification of superevents at 1 AU in particular, where the presence of such events can be obscured by the background of quasi-continuous SEP activity during solar maximum. The successively shorter averaging times used with increasing radial distances reflect the simplification in particle profiles that occurs in the outer heliosphere [*Pyle et al.*, 1979, 1984; *McDonald et al.*, 1981*b*].

Dröge et al. [1992] identified 16 superevents observed at all three spacecraft during the interval from 1974 to 1985. In this study we will focus on six of the most prominent superevents (cross-hatched at P-10 in Figure 1) observed throughout this period: numbers 1, 4, 7, 10, 13, and 16. These events correspond, for the most part, to the large superevents reported by *Müller-Mellin et al.* [1986]. They have several distinguishing characteristics. First, *Akioka et al.* [1992] have recently shown that the intense superevents observed in cycle 21 (numbers 4, 7, 10, 13, and 16) occurred near the maxima of large-amplitude pulses in sunspot areas of solar "hot spots", i.e., active longitudes. Second, the six superevents under consideration tended to be associated with strong interplanetary shock waves at P-11 and P-10 (P-11, four of six associated, median $\Delta v = 125$ km s^{-1}; P-10, five of six associated, median $\Delta v = 90$ km s^{-1}). Shock data obtained by *Mihalov* [1985, also private communication, 1992] and *Kayser* [1985] are given in Table 1. Third, the six superevents are closely matched to the subset of all superevents accompanied by relativistic electrons at P-10 (Figure 1); all but one of the six has an associated MeV electron event. *Lopate* [1989] has shown that the shocks associated with relativistic electron events are particularly strong, with compression ratios > 3 and velocity jumps ≥ 50 km s^{-1}.

2.2. Intervals

2.2.1. *September 1974.* The minicycle of cosmic ray modulation in 1974 during the solar activity minimum following the maximum of cycle 20 has been discussed by *Garcia-Munoz et al.* [1977]. An expanded view of this minicycle is given in Figure 2, where 4-day averages of the Deep River neutron monitor trace are plotted above 3-day averages of the 11- to 20-MeV proton fluxes measured at IMP 8, P-11, and P-10. The cutoff rigidity at Deep River is ~1.1 GV [*Shea et al.*, 1990]. The distance between tick marks on the *y* axis of the proton intensity plots in Figure 2 (and also Figures 3 through 7) represents 5 orders of magnitude. The two major peaks in the IMP 8 data in 1974, occurring in July (1974.5) and September (1974.7), originated in activity from McMath regions 13043 and 13225, respectively. Both of these regions originated at low latitudes (<20°), and the particle events represent the last major SEP activity of solar cycle 20 (Figure 1). In our comparisons of the Deep River and SEP data for this and subsequent events, we will focus on the 10-MeV proton profile at P-10; high peak fluxes at this increasingly distant spacecraft presumably signal the strongest transient disturbances of the heliosphere. Note that at P-10 (and also IMP 8) the September superevent is approximately 2 orders of magnitude more intense than any event associated with the principal decrease of cosmic ray intensity that occurred from February through June. Yet the September event does not lead to a further long-term decrease in the Deep River neutron monitor count rate, at least not to a decrease commensurate with the size of the SEP event. The recovery of the minicycle begins sometime during the July-September interval of high SEP activity and is complete by mid-1975. This superevent differs from the other events in Table 1 in that the proton increases at P-11 and P-10 were not associated with strong interplanetary shocks (J. Mihalov, private communication, 1992). This is somewhat surprising because the major activity from Mc-

TABLE 1. Shocks at P-10 and P-11 Associated with Prominent Superevents, 1974 to 1985

Superevent	Activity Interval	$\Delta\phi$ P-11 − P-10	P-11 Date	P-11 $\Delta V(\frac{km}{s})$	P-11 Ref.	P-10 Date	P-10 $\Delta V(\frac{km}{s})$	P-10 Ref.
1	Sept. 1974	10	–	–	1	–	–	1
4	April-May 1978	95	May 11	170	2	May 27	120	3
						June 5	20	2
7	Aug.-Sept. 1979	110	Sept. 26	80	2	Sept. 27	20	2
						Oct. 26	30	4
10	April-May 1981	140	June 3	190	2	June 20	90	4
13	June-July 1982	155	Aug. 2	80	4, 5	July 29	230	4
16	April 1984	170	–	–	–	July 7	80	1

References: 1, J. Mihalov [private communication, 1992]; 2, *Mihalov*, [1985]; 3, *McDonald et al.* [1981*c*, *d*]; 4, *Kayser* [1985]; 5, *Cliver et al.* [1987].

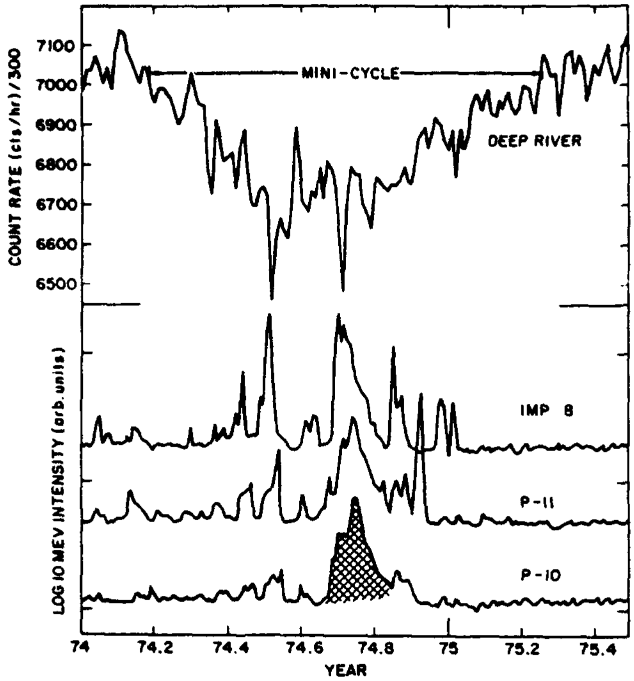

Fig. 2. Deep River neutron monitor count rate (4-day averages) and 10-MeV proton fluxes (3-day averages) at IMP 8, P-11, and P-10, January 1974 to June 1975. Superevent 1 is indicated by cross-hatching in the P-10 trace.

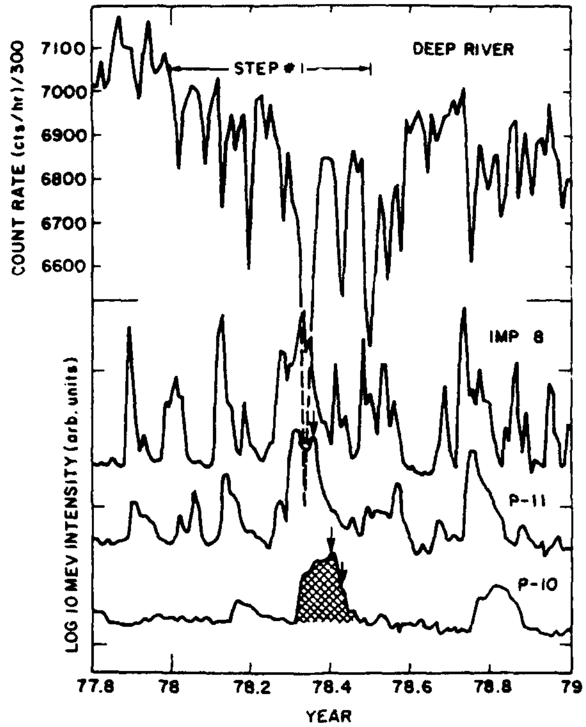

Fig. 3. Deep River neutron monitor count rate (4-day averages) and 10-MeV proton fluxes (3-day averages) at IMP 8, P-11, and P-10, October 1977 to December 1978. Superevent 4 is indicated by cross-hatching in the P-10 trace. Arrows mark the times of significant interplanetary shocks at P-11 and P-10 during the superevent.

Math 13225 encompassed the ecliptic longitudes of P-10 and P-11, and a sudden commencement and Forbush decrease were observed at 1 AU on 15 September when earth was located within ~5° in azimuth of both P-11 and P-10.

2.2.2. *April-May 1978.* GCR modulation during solar cycle 21 began in January 1978 with a steplike decrease of intensity (step 1 in Figure 3) that lasted for approximately one half year during which the Deep River intensity dropped from an average value of ~7050 (cts/h)/300 to ~6650 (cts/h)/300. Superevent 4, corresponding primarily to intense activity from McMath 15266 in April and May (1978.3-1978.4), is associated with a sharp decrease in the count rate from ~6900 (cts/h)/300 to ~6050 (cts/h)/300. The average GCR intensity recovered rapidly to an average value of ~6700 (cts/h)/300, however, and the decrease associated with the superevent appears to be superposed on the more gradual long-term decrease. The time profile of >75 MeV/nucleon GCRs at Voyager 2 at ~3 AU [*Burlaga et al.*, 1984] also gives the impression of a short-term decrease riding on a longer-term decline (cf. *McDonald et al.*, 1981*d*). At P-10, the 10-MeV superevent is more than 1 order of magnitude larger than any event associated with the onset of the step decrease. This is also the case for proton energies of ~1 MeV [*McDonald et al.*, 1981*b*]. Powerful shocks with $\Delta v > 100$ km s^{-1} were observed at both P-11 and P-10 in conjunction with the superevent (Table 1).

2.2.3. *August-September 1979.* The second long-term GCR decrease (step 2) of cycle 21 began in late 1978 and lasted until August-September 1979, when the GCR intensity bottomed out and began recovery to a plateau level, where it remained for the rest of the year (Figure 4). Superevent 7 in August-September (~1979.6-1979.8) corresponds to two marked, but short-lived, intensity decreases in the neutron monitor data. The causative solar events for this superevent originated in a limited range of Carrington

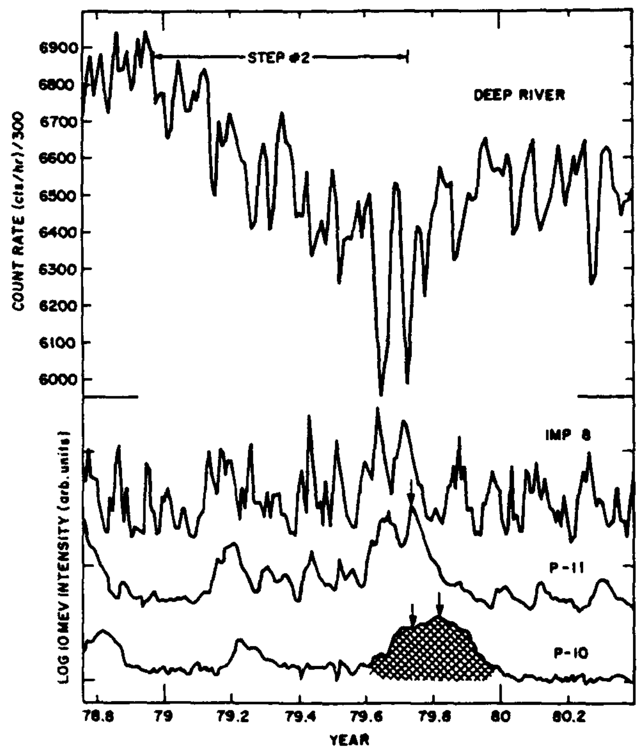

Fig. 4. Deep River neutron monitor count rate (4-day averages) and 10-MeV proton fluxes (3-day averages) at IMP 8, P-11, and P-10, October 1978 to May 1980. Superevent 7 is indicated by cross-hatching in the P-10 trace. Arrows mark the times of significant interplanetary shocks at P-11 and P-10 during the superevent.

longitudes (McMath 16239 and its return as 16298), and solar rotation produced a quasi-symmetric distribution of events in the ecliptic plane [*Dröge et al.*, 1992]. In the P-10 10-MeV proton record, superevent 7 is nearly 1 order of magnitude more intense than any activity (including superevent 6, Figure 1) occurring during the principal GCR intensity decrease from December 1978 to July 1979 [cf. *McDonald et al.*, 1981*b*]. Superevent 7 is similar to the 1974 superevent in that a marked enhancement in SEP activity signaled the end of a GCR intensity decrease. A strong shock ($\Delta v \sim 80$ km s^{-1}) was observed at the peak of the superevent at P-11; a smaller shock ($\Delta v \sim 20$ km s^{-1}) and candidate shock ($\Delta v \sim 30$ km s^{-1}) were observed at P-10 (Table 1). Examination of the modulation record at P-10 at ~20 AU given by *McDonald et al.* [1981*d*] shows that the superevent peak in October 1979 in Figure 4 occurs near the end of the long-term modulation step observed at that spacecraft.

2.2.4. *April-May 1981.* Step 3 in the GCR intensity profile at 1 AU during cycle 21 began in April 1980 (1980.3) and was essentially complete by the end of the year (Figure 5). Throughout 1981 the Deep River GCR trace can be characterized as a plateau at ~6100 (cts/h)/300 with fluctuations of ~250 (cts/h)/300. Superevent 10 originated during this plateau period in a concentration of SEP flare activity lasting from late March through mid-May (~1981.2-1981.4). During this period, major events arose from four distinct longitude bands; the most prolific of these bands corresponded to active region 17535 and its successors [*Dröge et al.*, 1992]. As can be seen in Figure 5, this activity resulted in a strong Forbush decrease at Deep River but no long-term change in the GCR intensity. Strong shocks with $\Delta v \sim 100$ km s^{-1} (Table 1) occurred near the maxima of the superevent at P-10 and P-11, located ~140° apart in heliolongitude. As at 1 AU, the superevent at P-10 (~25 AU) occurs at the end of, or following, step 3 in the modulation record at that satellite [*Burlaga et al.*, 1984, Figure 2]. *Mihalov* [1985] and *Kayser* [1985] report several additional shocks at P-11 and P-10 during the interval depicted in Figure 5. The most important of these shocks for long-term modulation appears to be the event observed on August 18, 1980 at P-10, indicated by the dashed arrow [*Kayser*, 1985; *McDonald et al.*, 1981*d*; *Burlaga et al.*, 1984; *Webber et al.*, 1986]. *Webber et al.* [1986] trace this event back to a Forbush decrease at earth in early June, and *Burlaga et al.* [1983, 1984] identify the central element in the corresponding compound flow seen at Voyager 1 as a high-speed corotating stream with maximum at Helios 1 on June 12 that swept up numerous small transient streams as it propagated to Voyager 1. Only weak SEP activity was observed at 1 AU in May and June 1980 (Figure 5).

At P-10, the 10-MeV proton intensity of the 1981 superevent is about 2 orders of magnitude more intense than any activity, including superevents 8 and 9 (Figure 1), occurring during the 1980 step decrease. At 3 to 5 MeV, the ratio of the rotation-averaged intensity of superevent 10 to

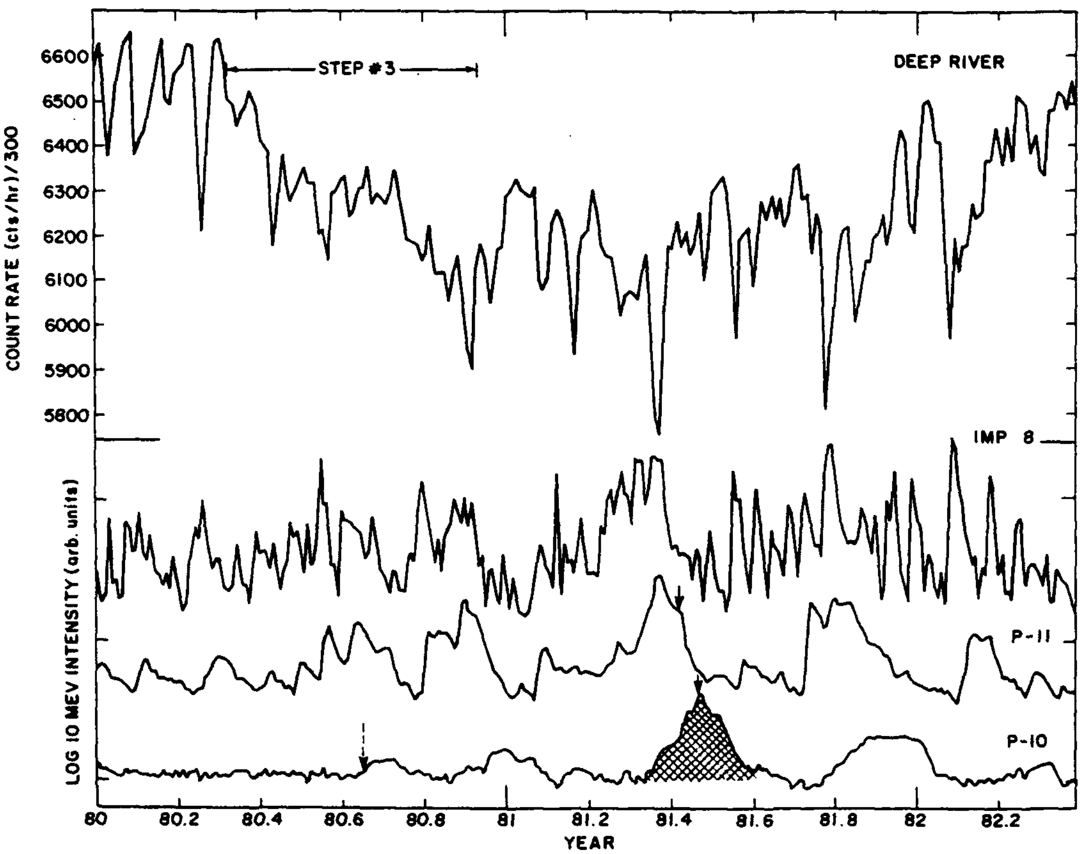

Fig. 5. Deep River neutron monitor count rate (4-day averages) and 10-MeV proton fluxes (3-day averages) at IMP 8, P-11, and P-10, January 1980 to May 1982. Superevent 10 is indicated by cross-hatching in the P-10 trace. Arrows mark the times of significant interplanetary shocks at P-11 and P-10 during the superevent. The dashed arrow corresponds to a shock associated with the onset of the modulation step.

preceding activity is >20:1 [*McDonald and Selesnick*, 1991]. The relative deficit of interplanetary protons during 1980 has been documented by *Van Allen and Decker* [1988].

2.2.5. *June–July 1982.* Solar activity and cosmic ray modulation in June–July 1982 has been discussed in detail by *Cliver et al.* [1987]. In this event, increased SEP activity leading to superevent 13 is clearly associated with the onset of a modulation step (step 4 in Figure 6) at 1 AU, as well as in the outer heliosphere [*Pyle et al.*, 1984]. This GCR intensity decrease represents the superposition of a step decrease and the recovery from earlier GMIRs [*McDonald et al.*, 1991]. The SEP activity during this period was associated mainly with a series of flares from active regions 18382/18383 (N15–20; Carrington longitude = 310°) in early June and Hale 18405 (N10–20; Carrington longitude = 320°) in July. A spectacular shock ($\Delta v \sim 230$ km s^{-1}) was observed at P-10 [*Pyle et al.*, 1984; *Kayser*, 1985] at the peak of the superevent, and a notable event ($\Delta v \sim 80$ km s^{-1}) was observed 5 days later at P-11, separated by 155° in heliolongitude (Table 1). Two other weaker shocks were also observed at P-11 during this event (Figure 6). For the June–September period, *Lockwood and Webber* [1984] reported that the modulation propagated outward with a speed of 790±150 km s^{-1}.

Note that superevent 14, associated with intense solar activity in November–December 1982, results in only a temporary halt to the GCR recovery that began in October 1982 (Figure 6). Shocks and probable shocks (during data gaps) observed in the outer heliosphere in conjunction with the November–December activity occurred on December 26–27 and January 12–13 at P-11, and on January 17 and March 9–10 at P-10 [*Kayser*, 1985; J. Mihalov, private communication, 1992].

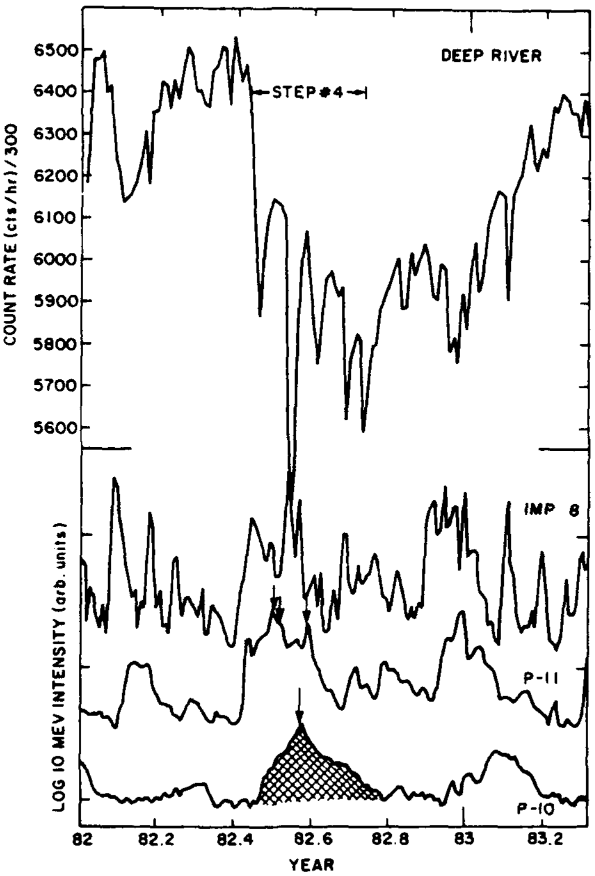

Fig. 6. Deep River neutron monitor count rate (4-day averages) and 10-MeV proton fluxes (3-day averages) at IMP 8, P-11, and P-10, January 1982 to April 1983. Superevent 13 is indicated by cross-hatching in the P-10 trace. Arrows mark the times of significant interplanetary shocks at P-11 and P-10 during the superevent.

2.2.6. *April–May 1984.* Superevent 16, associated with activity from NOAA active region 4474 in late April and its return as 4492 in May (~1984.3–1984.4), occurred during a step decrease superimposed on the long-term recovery following the maximum of cycle 21 (step 5 in Figure 7). This event is similar to the April–May 1978 superevent in that the intense solar activity and associated Forbush decrease occurred following the onset of a GCR intensity decrease, which began in February 1984 in this case. The principal decrease during this step [~200 of the total ~300 (cts/h)/300 drop] is associated with the superevent. A strong shock is observed in conjunction with this superevent at P-10 but not at P-11, even though the P-11 data are reasonably complete for this period. A shock with $\Delta v > 100$ km s^{-1} is observed at P-11 on April 15 (dashed arrow in Figure 7) in association with a large SEP event preceding the superevent. The April 15 shock most probably originated in SEP activity in mid-March. In the 10-MeV proton profile at P-10, there is only a weak rise or "shoulder" corresponding to the onset of the step at 1 AU.

3. DISCUSSION

3.1. *Summary of Observational Results*

We examined the intensity variation of >1-GV galactic cosmic rays at 1 AU at the times of six prominent superevents [*Müller-Mellin et al.*, 1986; *Dröge et al.*, 1992] observed from 1974 to 1985. The superevents were characterized by strong shocks ($\Delta v \sim 100$ km s^{-1}) and relativistic electron events in the outer heliosphere and thus represent strong transient disturbances. In general, the superevents did not signal long-term decreases in the Deep River neutron monitor count rate. Of the six cases examined, in only one (June–July 1982) did the superevent occur at the onset of a step decrease in the GCR intensity. In that case modulation propagated to the outer heliosphere at ~800 km s^{-1} [*Lockwood and Webber*, 1984; cf. *Cliver et al.*,1987]. In two cases, a superevent and associated short-term decrease occurred when a step was in progress. In the remaining three cases, a superevent occurred at the end of, or following, a step and no additional long-term decrease was observed. For two of these three cases (July–September 1974, April–May 1981), the superevent 10-MeV peak fluxes at P-10 were approximately 2 orders of magnitude greater than that of any particle activity associated with the onset of the step. While our analysis was confined to the effect of major superevents on modulation at 1 AU, comparisons of superevent profiles with published GCR intensity data from deep-space probes show, in general, that these superevents were not closely related to the onsets of modulation steps observed out to ~30 AU during this period.

3.2. *Superevents and Modulation Steps in Other Cycles*

GCR modulation steps have also been identified in cycles 18, 19, and 22.

Morrison [1956] identified two such steps in cycle 18: Feb–

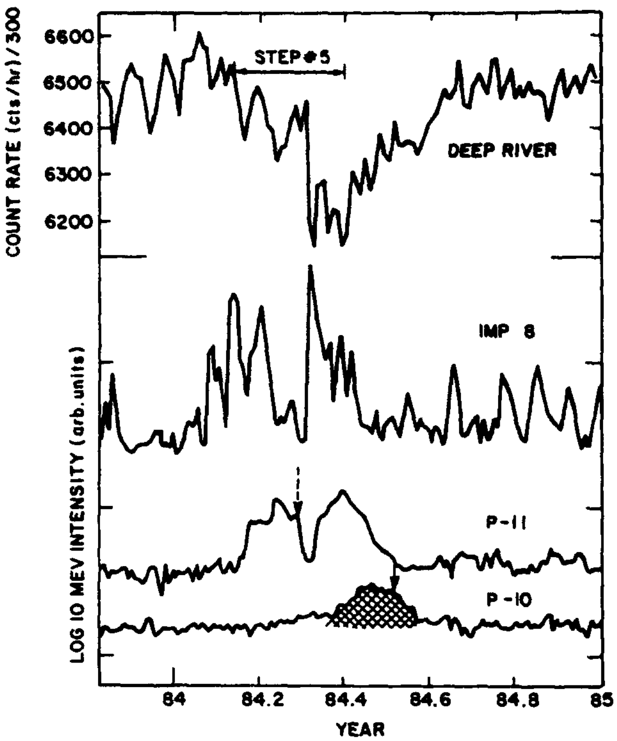

Fig. 7. Deep River neutron monitor count rate (4-day averages) and 10-MeV proton fluxes (3-day averages) at IMP 8, P-11, and P-10, November 1983 to December 1984. Superevent 16 is indicated by cross-hatching in the P-10 trace. An arrow on the P-10 trace marks the time of an interplanetary shock. The dashed arrow indicates a prominent shock at P-11 preceding the superevent.

ruary 1946 and March–July 1947. There is indirect evidence [*Svestka*, 1966], based on high-latitude vertical-incidence ionosonde data, for SEP events near the onset of both of these steps, but the existing data are, in our opinion, insufficient to establish or rule out concomitant superevents in either case.

The principal step decreases in GCR intensity during solar cycle 19 occurred in November 1955, November 1956 through January 1957, and August–December 1957 [*Lockwood*, 1960]. Examination of the pertinent flare [*Dodson and Hedeman*, 1971; *Dodson et al.*, 1974] and SEP [*Svestka and Simon*, 1975] records leads us to conclude that the association of superevents with these decreases is unlikely for the first step, questionable for the second step, and virtually certain for the third step. Yet the ratios of the net decreases (percentage drops) during the three modulation steps were roughly 1:2:1 as seen in Mount Washington [*Lockwood and Webber*, 1984] and Climax [*Lopate and Simpson*, 1991*a*] neutron monitor data. Thus there is no clear relationship in these cases between the level of SEP activity and the associated long-term GCR intensity decrease.

This is underscored by the fact that the two periods of the most intense and long-lived SEP activity of cycle 19 (July 1959 and November 1960 [see *Svestka and Simon*, 1975, and references therein]) failed to produce any long-term decrease in the GCR intensity. Both of these periods had >10-MeV SEP fluences $>10^{10}$ pr cm^{-2}[*Shea and Smart*, 1990], placing them in the top five "events" in terms of this parameter for the 1942–1992 period (M. A. Shea, private communication, 1992). For the July 1959 event, the GCR intensity at 1 AU had essentially recovered within 4 months; recovery in November 1960 was complete within 1 month. Similarly, the August 1972 SEP activity in cycle 20, a high-fluence period ($>10^{10}$ pr cm^{-2}) that should also be considered a superevent (profile in *Van Hollebeke et al.* [1974]), resulted in only a temporary (~1-month) drop in the GCR intensity at 1 AU.

The first global merged interaction region (global step decrease) identified during solar cycle 22 was observed at 1 AU in early January 1989, at Voyager 2 (≈28 AU) on day ≈65, and at Voyager 1 (≈37 AU) on day ≈125 [*Webber and Lockwood*, 1990; *Burlaga et al.*, 1993; *McDonald et al.*, 1993]. We note that this step decrease lagged a few months behind a sharp increase in the overall CME rate in late September 1988 [*Cliver and Kahler*, 1991] and preceded by 2 months the first major SEP activity, and first prominent superevent, of cycle 22, arising in early March 1989 in NOAA active region 5395.

3.3. Superevents and GMIRs

McDonald et al. [1981*a*] observed that GCR modulation in cycle 21 occurred in a series of steps, and *Burlaga et al.* [1984, 1985] identified these steps with MIRs, subsequently called GMIRs [*McDonald et al.*, 1991, 1993; *Burlaga et al.*, 1993]. Because they originate in episodes of fast CMEs and can involve systems of strong shocks that encompass the sun, it is attractive to view superevents as signatures of GMIRs [*Flückiger*, 1991; *Dröge et al.*, 1992]. Our study shows that the most intense superevents from 1974 to 1985 were neither necessary nor sufficient preconditions for step decreases in the GCR intensity at 1 AU. During this interval we find that (1) prominent superevents may occur anywhere within modulation steps and (2) there is no apparent relationship between the amplitude of a GCR decrease and the intensity of any associated ~10-MeV SEP activity. Thus superevents and GMIRs do not appear to be closely related. This does not preclude a "loose" association or some overlap in time between steps and superevents at a given radial distance; such a relationship is inevitable given that both phenomena are relatively long-lived and tend to occur near solar maximum. The lack of a well-defined relationship between superevents and steps is illustrated by the recent work of *McDonald et al.* [1993] in which three GMIRs (revealed by low-energy particle increases) are identified during 1989–1990 at P-10 in comparison with only two steps during the same interval.

The data indicate that in certain cases, such as July 1959 and June–July 1982, the solar activity associated with superevents may give rise to modulation steps. Modulation associated with the intense SEP activity in June 1991 also appears to fit this category, since the associated disturbance propagated to P-11 and P-10 with a speed of ~800 km s^{-1} [*Van Allen and Fillius*, 1992].

Burlaga et al. [1986] examined the "compound" solar wind stream associated with the latter part of the August–September 1979 superevent and noted that it was not associated with any long-term decrease in GCR intensity. They concluded that the GCR intensity at Voyager 2 recovered rapidly following the passage of this stream because the stream was limited in azimuth, allowing incoming GCRs to quickly "backfill" around the barrier. The analysis of *Dröge et al.* [1992] on the locations of the associated solar events and also on the variation of particle intensity at

1 AU with heliospheric longitude indicates that the activity was widespread in longitude. P-10 and P-11 were separated by ~110 ° at this time (Table 1, column 3) and the event is prominent at both spacecraft (Figure 4). For the April-May 1981 superevent, which was similarly prominent at both P-10 and P-11, the longitudinal separation between these spacecraft was ~140°. This event was also unaccompanied by any long-term decrease in GCR intensity. At both 1 AU (Figure 5) and P-10 [*Pyle et al.*, 1984, Figure 1], the April-May 1981 superevent occurs near the onset of recovery from the third step in cosmic ray modulation in cycle 21. The failure of the August-September 1979 and April-May 1981 superevents and their associated shocks to produce modulation steps might still be explained by a limited latitudinal extent of the causative CMEs.

3.4. A Role for Less Energetic CMEs

Burlaga et al. [1984] concluded that the relative importance of many small transients vs. a few large disturbances was an open question for the convection/diffusion picture of modulation [*Burlaga et al.*, 1985; *Perko and Burlaga*, 1992; *Burlaga et al.*, 1993; *McDonald et al.*, 1993]. Recent work indicating a link between GMIRs, modulation steps, and superevents [*Müller-Mellin et al.*, 1986; *Cliver et al.*, 1987; *McDonald and Selesnick*, 1991; *Flückiger*, 1991; *Dröge et al.*, 1992; *McDonald et al.*, 1993], has favored the role of major events, but, as we have shown for the interval from 1974 to 1985, there is no detailed correspondence between the occurrence of prominent superevents, which originate in intense SEP activity, and long-term modulation. In two of the cases we considered (1974 and 1980-1981), modulation steps occurred in concert with relatively weak particle activity at either IMP 8 or P-10. *Burlaga et al.* [1983, 1984] ascribe the rapid long-term decrease in GCR intensity in June 1980 to a series of small short-lived transient flows that are swept up or entrained by a corotating stream. These results suggest that the outbursts of sporadic SEP flare activity that give rise to superevents are less important for establishing the long-term modulation of cosmic rays than is the "background" of less energetic and therefore more common [*Howard et al.*, 1985] CMEs, whose occurrence rate tracks the solar cycle [*Webb*, 1991]. This conjecture will need to be checked by a detailed comparison of CME rates and properties, e.g., speeds and latitudes, with the GCR modulation record. In its support at present, we note that the rotation-averaged rate of all CMEs over the maximum of cycle 21 (~1.5 CME/day [*Howard et al.*, 1985]) is 3 to 8 times the rate of the major (as defined by *Dröge et al.* [1992]) solar events observed in conjunction with superevents. The fact that the lengths of modulation steps (or the decay phase of minicycles) are typically ~6 months (Figures 2 through 7) while the episodes of major activity giving rise to superevents have durations ranging from 2 weeks to 2 months also indicates a role for weaker CME activity not associated with superevents. In addition, the speed at which modulation propagated to the outer heliosphere during much of cycle 21 (550 km s^{-1} [*McDonald et al.*, 1981*a*], or 350-500 km s^{-1} [*Lockwood and Webber*, 1984]) is more representative of normal solar wind flows than of the transit speeds of superevents and fast interplanetary shocks. This is consistent with modulation resulting from less energetic, more typical CMEs. The median speed of CMEs observed by Solwind from 1979 to 1981 was ~200 km s^{-1} [*Howard et al.*, 1985].

3.5. Drift Effects

Smith and Thomas [1986] have shown that the steplike decreases in the GCR intensity during cycle 21 were preceded by steplike increases in the tilt angle of the heliospheric current sheet. Similarly, *Saito and Swinson* [1986] showed that the modulation minicycles in 1973 and 1974 during cycle 20 followed poleward excursions of the coronal streamer belt. Thus particle drifts in large-scale heliospheric fields [*Jokipii et al.*, 1977; *Kota and Jokipii*, 1983; *Smith*, 1990; *Lopate and Simpson*, 1991*b*; *Potgieter and Le Roux*, 1992] may also contribute to long-term modulation. In particular, we note that drift-imposed particle entry into the heliosphere, inward along the poles during qA > 0 cycles (for positively charged particles) and inward along the heliospheric current sheet during qA < 0 cycles, may make the relatively low-latitude SEP-flare activity associated with superevents more effective for modulation during qA < 0 cycles. *McDonald et al.* [1993] have recently invoked large-scale drifts to account for the absence of "backfilling" at Voyager 2 during the step decrease beginning in 1987 [*Burlaga et al.*, 1991, 1993) that was not observed at Voyager 1, then located ~ 30° above the ecliptic plane. Of the intense superevents from 1974 to 1985 that we considered, the two that were most effective in terms of modulation, June-July 1982 and April-May 1984, occurred during the qA negative cycle that began in 1980.

3.6. Conclusions

The primary results and implications of this study are as follows. (1) Superevents are not reliable signatures of GMIRs. This could occur because the inferred azimuthal symmetry of superevents does not translate, in general, to the quasi-spherical symmetry required for GMIRs. (2) The major solar/interplanetary events that are the constituents of superevents do not "drive" the 11-year modulation cycle. In the context of diffusion/convection models, this suggests that the background level of less energetic CMEs, which rises and falls with the solar cycle, plays a key role in long-term modulation.

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